REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Washington Headquarters Service, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT DATE	3. DATES COVERED *(From - To)*
08-08-2002		11-30-98 / 12-31-01

4. TITLE AND SUBTITLE
Internal Waves over the New England Shelf

5a. CONTRACT NUMBER

5b. GRANT NUMBER
N00014-99-1-0178 and 0180

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Albert J. Plueddemann
Craig M. Lee

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Department of Physical Oceanography
Woods Hole Oceanographic Institution
Woods Hole MA 02543
Craig M. Lee Applied Physics Lab. Univ. of Washington
Seattle, WA 98105

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
ONR
Ballston Centre Tower One
800 North Quincy Street
Arlington, VA 22217

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE - DISTRIBUTION IS UNLIMITED

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This study focused on investigating several aspects of the internal wave field over the New England Shelf, considered to be representative of a general class of broad, gently-sloping shelves. Specifically, we worked to characterize the horizontal and vertical structure of the internal wave field over the shelf and to examine how coastal geometry, stratification and background flow act to modify the near-inertial response to impulsive wind forcing.

15. SUBJECT TERMS

20020815 088

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
FINAL			UL	7	Albert Plueddemann
					19b. TELEPONE NUMBER *(Include area code)* 508-289-2789

Internal Waves Over the New England Shelf

Albert J. Plueddemann
Department of Physical Oceanography, MS-29
Woods Hole Oceanographic Institution
Woods Hole, MA 02543
Phone: (508) 289-2789; Fax: (508) 457-2181
aplueddemann@whoi.edu

Craig M. Lee
University of Washington
Applied Physics Laboratory
1013 NE 40th St.
Seattle, WA 98105-6698
Phone: (206) 685-7656; Fax: (206) 543-6785
craig@apl.washington.edu

Award Number: N00014-99-1-0178 (AJP); N00014-99-1-0180 (CML)

LONG-TERM GOALS

Our long-term goal is to better understand processes controlling the horizontal and vertical distribution of internal wave energy over the continental shelf. Emphasis will be placed on the near-inertial band. Both the initial response to impulsive forcing and the overall distribution of near-inertial energy are of interest.

OBJECTIVES

This study focused on investigating several aspects of the internal wave field over the New England Shelf, considered to be representative of a general class of broad, gently-sloping shelves. Specifically, we worked to characterize the horizontal and vertical structure of the internal wave field over the shelf and to examine how coastal geometry, stratification, and background flow act to modify the near-inertial response to impulsive wind forcing.

APPROACH

The project combined analytical modeling and the analysis of archived measurements to further our understanding of the processes governing near-inertial internal wave variability over the shelf. Analytical models based on the two-layer formulation of Pettigrew (1980) and Millot and Crepon (1981) were developed and used as a guide to interpreting the observations. Characteristics of the internal wave field were documented and the near-inertial signal isolated using data from the Nantucket Shoals Flux Experiment (NSFE) and the combined Coastal Mixing and Optics (CMO) and Shelf Break PRIMER experiments. Due to differences in instrumentation and array geometry, the NSFE data are best suited to examine horizontal variability while the CMO/PRIMER observations were used to study both vertical and horizontal structure. Surface forcing was available from in-situ

measurements during both NSFE and CMO/PRIMER. In addition, two-dimensional maps of mesoscale atmospheric fields were available for CMO/PRIMER (Baumgartner and Anderson, 1999).

WORK COMPLETED

The complete NSFE data were obtained and reformatted for analysis, and Acoustic Doppler Current Profiler (ADCP) records from Shelfbreak PRIMER were combined with current meter data from the CMO moored array. The near-inertial signal was isolated from NSFE and CMO/PRIMER current meter data by removing the dominant barotropic tidal constituents and band-pass filtering the resulting record. The resulting near-inertial velocities were then examined in conjunction with surface forcing fields to identify individual forcing events that evoked strong near-inertial responses. For NSFE, events warranting further study were identified following Wood and Chapman (1989). Aspects of surface forcing relevant to analytical modeling (length scale, translation speed and duration of storms and fronts) were determined for CMO/PRIMER using the buoy meteorology and the regional model results described by Baumgartner and Anderson (1999). The episodic nature of near-inertial internal wave generation motivated an event-driven analysis.

A hierarchy of analytical models (of increasing complexity) based on the two-layer formulations of Pettigrew (1980) and Millot and Crepon (1981) were developed as aids to understanding the observed response. The impulsive forcing (delta function) case described by Pettigrew (1980) was re-derived and extended to include both offshore-propagating step function forcing (representing the leading edge of a front) and offshore-propagating pulse forcing (representing the leading and trailing edges of a storm system). A close examination of CMO atmospheric model results indicated that many strong atmospheric systems propagated northward and eastward alongshore, rather than offshore. This forcing configuration was thus added to the model.

RESULTS

The near-inertial signals extracted from both NSFE and CMO/PRIMER show responses to surface forcing which can be approximated as a two-layer flow. Comparing near-inertial currents near the surface with those near the bottom highlights this quasi two-layer response. There is a tendency for oscillations in the upper and lower layers to be approximately out of phase, although many events show phase variability. Four typical cases can be distinguished based on the relative phase and strength of currents in each layer (Figure 1). As anticipated, much of the variability is related to changes in the background stratification (Lentz et al., in press). Heating in spring and summer results in a thin surface layer and enhanced upper layer currents (Figure 1a). In fall and winter the pycnocline is eroded by growing surface and bottom mixed layers, creating nearly equal layer thicknesses and current amplitudes (Figure 1b). If mixing is strong enough, the water column may be well mixed, resulting in currents which are nearly in-phase and comparable in amplitude (Figure 1c). At other times near-bottom intrusions of slope water can create a thin lower layer, resulting in enhanced lower layer currents (Figure 1d).

Surface meteorology from the Eta-29 model described by Baumgartner and Anderson (1999) shows that propagating low-pressure systems often control wind variability over the New England Shelf in fall and winter. The associated wind fields are typically of large scale (e.g., 350-550 km N/S by 450-700 km E/W), sufficient to encompass the eastern seaboard from Cape May (NJ) to Cape Cod (MA) and extend from the coast to the shelf break. The lows typically propagate from southwest to northeast,

resulting in a wind anomaly that propagates along-shelf and is quasi-uniform cross-shelf (Figure 2). The near-inertial responses shown for summer and winter CMO/PRIMER data (Figure 1a,b) arise from this type of forcing. Cross-shelf propagating fronts, as described by Kundu and Thompson (1985), are rare. Only two were identified in Eta model during CMO/PRIMER.

Simple extensions of the original two-dimensional, two-layer model (Pettigrew, 1980; Millot and Crepon, 1981) introduce considerable variability in the response. Following the original configuration, forcing the model with spatially uniform, impulse (delta function) offshore wind generates a response where upper and lower layer velocities are 180° out of phase (Figure 3). This two-layer structure is actually a superposition of upper-layer inertial oscillations driven directly by the wind and a barotropic response that propagates rapidly outward from the coast. A baroclinic response propagates away from the boundary more slowly and, at longer time scales, acts to modulate the response in both layers. The phase relationship between upper and lower layer currents is a characteristic of the two-layer response to spatially uniform impulse forcing, and is similar to several of the events identified in the observations.

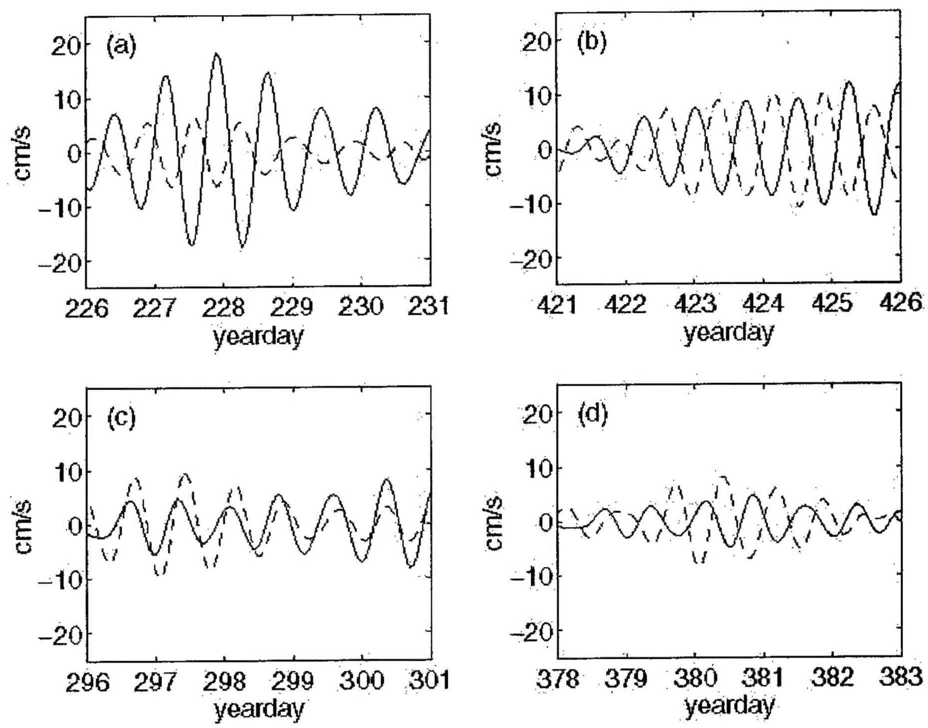

Figure 1. Observed inertial-band velocity responses from instruments near the surface (solid lines) and near the bottom (dashed lines) are shown for differing background stratifications. (a) CMO/PRIMER data in summer showing enhanced surface currents and variable phase through the event. (b) CMO/PRIMER data in winter showing nearly equal amplitude currents with phase near 180 degrees. (c) NSFE data in fall showing approximately in-phase response. (d) CMO/PRIMER data in winter showing enhanced bottom currents and variable phase.

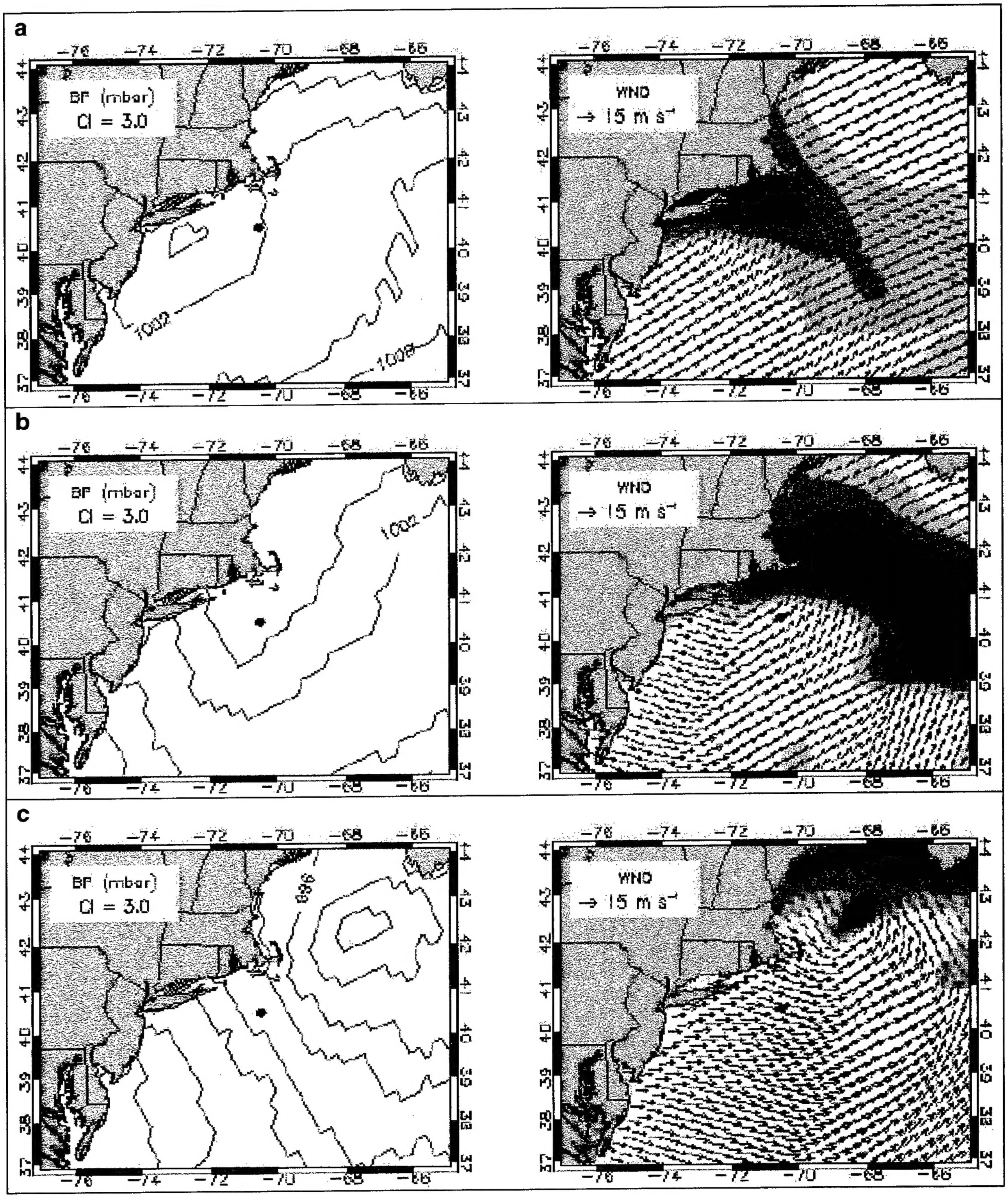

Figure 2. Eta model surface pressures and wind velocities (Baumgartner and Anderson, 1999) for 11 January, 1997 (a) 09:00, (b) 12:00 and (c) 18:00. A low pressure system moves northeast over the New England shelf, bringing strong winds with roughly uniform cross-shelf structure.

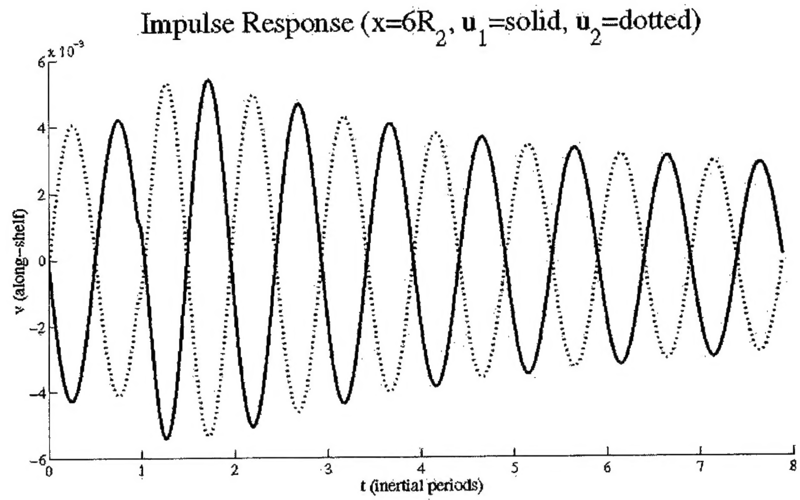

Figure 3. Along-shelf velocity for the upper (solid) and lower (dotted) layers of the two-layer model forced by a spatially uniform impulse wind. Layer depths are of equal thickness. Results are shown as a function of time at a location 6 internal Rossby radii from the coastal boundary. The barotropic response arrives almost instantaneously, while the baroclinic response requires nearly one inertial period to arrive from the coast.

To examine the effects of forcing by atmospheric fronts moving in both the offshore and alongshore directions, we derived solutions for forcing by a propagating pulse. Now, in addition to barotropic and baroclinic waves that propagate outward from the coast, the response includes effects associated with the leading and trailing edges of the atmospheric system. The response is sensitive both to the speed of the front relative to the barotropic wave speed and to the pulse duration. In these examples, upper and lower layers are of equal thickness and the inertial period is 18.2 hours.

For an offshore-propagating front translating more slowly than the barotropic wave speed (Figure 4a), both layers respond in phase with growing amplitude. Both leading and trailing edges of the pulse generate near-inertial waves, which propagate away from the pulse. Wave energy propagating back to the site from the receding pulse produces the continued (but decelerating) amplitude growth depicted by the model. When pulse duration is close to the inertial period, waves generated by the leading and trailing edges destructively interfere to produce a damped response (Figure 4b). In the unrealistic limit of a front translating much faster than the barotropic wave speed, the upper and lower layers begin out of phase, but drift back into phase over the course of several inertial periods (Figure 4c). Interestingly, lower layer amplitudes are larger than upper layer amplitudes. In contrast to the observations, which typically revealed out of phase upper- and lower-layer responses, for typical translation speeds, the offshore-propagating front models show in phase upper- and lower-layer responses.

Forcing with a cross-shelf uniform, finite-duration pulse produced an out of phase response more similar to the observations (Figure 4d). As might be anticipated, the amplitude response for the cross-shelf uniform, finite-duration pulse depends strongly on the pulse duration relative to the local inertial period. Pulses lasting an integral number of inertial periods produce a highly damped near-inertial response due to destructive interference between waves generated by the leading and trailing edge 'fronts' (Figure 4e). In contrast, pulses lasting half an inertial period produce constructive interference and correspondingly strong near-inertial motions (Figure 4f). Observed CMO wind events also exhibited considerable rotation, a characteristic not accounted for in these simple models. Thus, care is warranted when making direct comparisons between observed and modeled near-inertial responses.

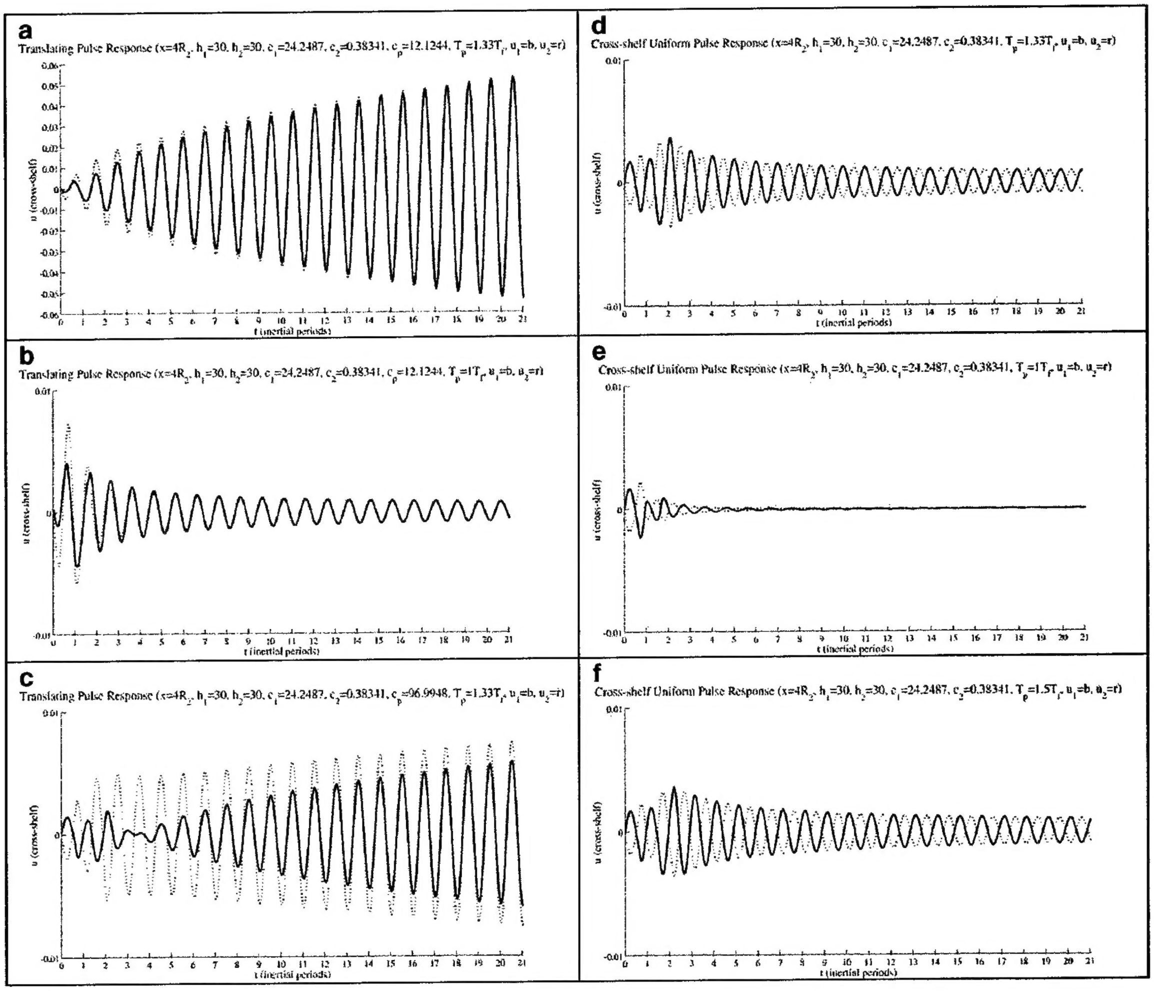

Figure 4. Along-shelf velocity for the upper (blue, solid) and lower (red, dotted) layers of the two-layer model forced by (a-c) an offshore translating wind pulse and (d-f) a cross-shelf uniform wind pulse. Layers are of equal thickness. Results are shown as a function of time at a location 4 internal Rossby radii from the coastal boundary. The barotropic response arrives almost instantaneously, while the baroclinic response requires approximately half an inertial period to reach this location from the coast. (a) Response for a pulse translating at half the barotropic wave speed, (b) As in (a), but for a pulse duration of one inertial period. Destructive interference between waves generated by the leading and trailing edges damps the response. (c) As in (a), but with unrealistically fast translation speed (much faster than the barotropic wave speed). (d) Response to forcing by a cross-shelf uniform pulse. (e) As in (d), but with pulse duration equal to one inertial period (destructive interference). (f) As in (d), but with pulse duration of 1.5 inertial periods, producing constructive interference and a slight amplification of the response.

IMPACT AND APPLICATIONS

By extending the analytical work done by previous investigators, we hope to elucidate the principal processes, which control the near-inertial response on broad, shallow shelves. Through comparison

with observations the ability of simple two-layer models to reproduce the observed response will be determined.

RELATIONSHIPS TO OTHER PROGRAMS

Archived data from NSFE (supported by the National Marine Fisheries Service, the U.S. Geological Survey, and the National Science Foundation), the CMO moored array (funded by the Office of Naval Research (ONR)), and the Shelfbreak PRIMER experiment (funded by ONR) were integrated in this study. Results will be shared with M. Levine and T. Boyd at Oregon State University who were funded by ONR to investigate the coastal internal wave field.

REFERENCES

Baumgartner, M. F., and S. P. Anderson, 1999. Evaluation of NCEP regional numerical weather prediction model surface fields over the Middle Atlantic Bight. J. Geophys. Res., 104(C8), 18,141-18,158.

Kundu, P. K., and R.E. Thompson, 1985. Inertial oscillations due to a moving front, J. Phys. Oceanogr., 15(8), 1076-1084.

Lentz, S., K. Shearman, S. Anderson, A. Plueddemann and J. Edson, The evolution of stratification over the New England Shelf during the Coastal Mixing and Optics study, August 1996 – June 1997, J. Geophys. Res., in press.

Millot, C., and M. Crepon, 1981. Inertial oscillations on the continental shelf of the Gulf of Lions - Observations and theory. J. Phys. Oceanogr., 11, 639-657.

Pettigrew, N. R., 1980. The dynamics and kinematics of the coastal boundary layer off Long Island. Ph.D. Thesis, MIT/WHOI Joint Program in Oceanography, Woods Hole, MA, 262 pp.

Wood, T. M., and D. C. Chapman, 1989. Observations of near-inertial motions during the Nantucket Shoals Flux Experiment. Unpublished manuscript, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts.